Interim Report
Deliverable 1.1:
RADAR Sensors for Transportation Applications of the Restricted Use Technology Study

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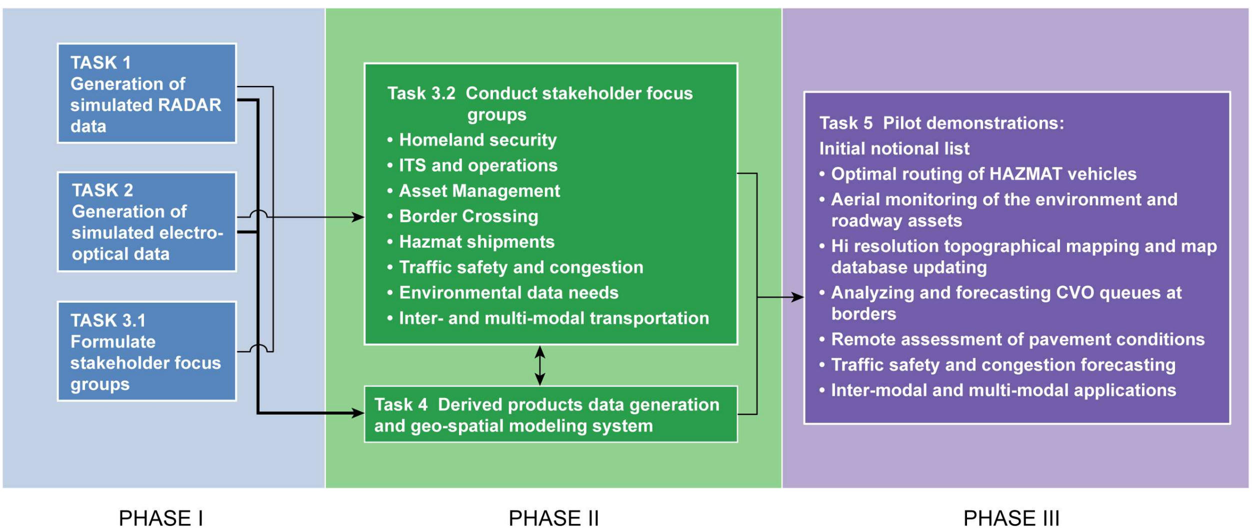
EXECUTIVE SUMMARY

The Altarum Institute, under contract to the Michigan Department of Transportation (MDOT), currently is engaged in a project called the "Altarum Restricted Use Technology Study." This study, an 18-month effort, seeks to apply restricted use technology to the mandates of MDOT. The major phases of this project are illustrated in Figure 1.

Under Deliverable 1.1 of the Work Plan governing the Altarum Restricted Use Technology Study, the Altarum project team is required to produce an unclassified summary and comprehensive written report of RADAR systems that can potentially address transportation problems. This report presents the fundamental concepts of RADAR operations, reviews the categories of civil, commercial and military sensors with their platforms, and discusses potential application areas of RADAR systems, both in general and those specific to transportation. Together with its companion report on electro-optical systems (Deliverable 2.1), this report will provide transportation experts with an overview of current resources and a foundation of potential applications.

Figure 1: Task Dependency within the Restricted Use Technology Study



RADAR based systems have evolved greatly since their initial development in the 1930s. Modern RADAR systems can provide high resolution imagery in all kinds of weather conditions, day or night. RADAR is also capable of mapping topography, detecting subsurface features, and measuring movement, either gradual as in the case of land subsidence, or rapid as in the case of moving vehicles. RADAR systems may be divided into several major groups, including:

- Synthetic Aperture RADAR (SAR)
- Interferometric SAR (InSAR)
- Pass to pass coherent SAR
- Ground moving target indicators (GMTI)
- Ground penetrating RADAR (GPR)

Many of these sensors can be found on a wide range of platforms including earth-orbiting satellites, manned aircraft, and unmanned aerial vehicles (UAVs).

RADAR systems have proved their value for military surveillance, environmental research, and a variety of civil applications. As discussed in this report, RADAR systems have great potential for addressing transportation needs in areas of:

- Asset Management
- Environmental Applications
- Inter- and Multi-modal Applications
- HAZMAT Shipments
- Traffic Congestion and Safety
- Border Crossings
- Homeland Security
- ITS and Operations

The Altarum team has completed this task, though the report will evolve by updates and revisions as the project progresses. The information discussed in this report will support the follow-on task of generating simulated RADAR data and will provide background information for the focus group sessions anticipated to be held in early 2006.

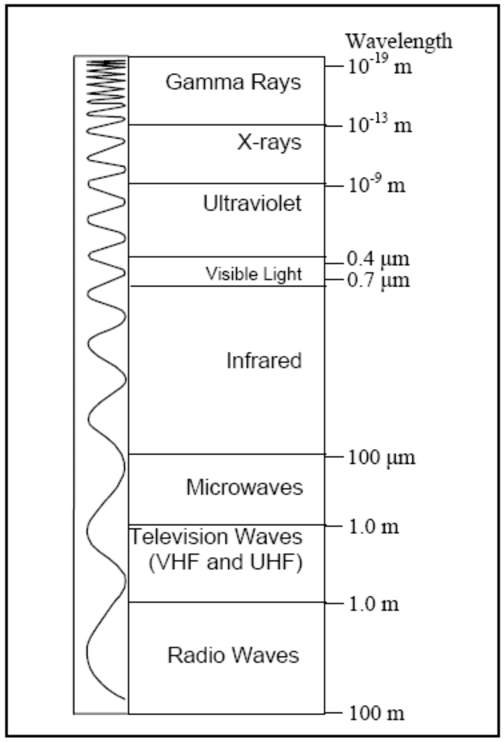
INTRODUCTION TO RADAR SENSORS

Remote sensing describes the collection of data about an object, area, or phenomenon from a distance with a device that is not in contact with the object. More commonly, the term remote sensing refers to imagery and image information derived by UAVs, manned airborne, and satellite platforms that house sensor equipment. The data collected by the sensors are in the form of electromagnetic (EM) energy. Electromagnetic energy is the energy emitted, absorbed, or reflected by objects. Electromagnetic energy is synonymous to many terms, including electromagnetic radiation, radiant energy, energy, and radiation.

A specialized form of remote sensing sensor is RADAR, which is an acronym for Radio Detection and Ranging. A RADAR instrument emits a pulse of electromagnetic energy, at the speed of light, and measures the time for the pulse to return. Distance is calculated from the travel time of the pulse. The distance and the strength of return, provides information on location and surface roughness of the feature of interest.

RADAR is an active form (meaning it carries its own source of electromagnetic radiation) of remote sensing, which operates in the microwave region of the electromagnetic spectrum (Figure 2). Table 1 lists the wavelengths of various bands used by RADAR systems. As indicated in the table, the microwave band spans 1 cm to 1 m. The RADARs presented in this report operate at X, C, L, and P bands (Table 1).

Figure 2: Electromagnetic Spectrum on a Vertical Scale.
Source: Corps of Engineers, 2003



The conversion of frequency to wavelength is provided by the well-known equation:

$$c = \lambda v$$

where

$c = 3.00 \times 10^8$ m/s, the speed of light

λ = wavelength (m), and

v = frequency (cycles/second, Hz)

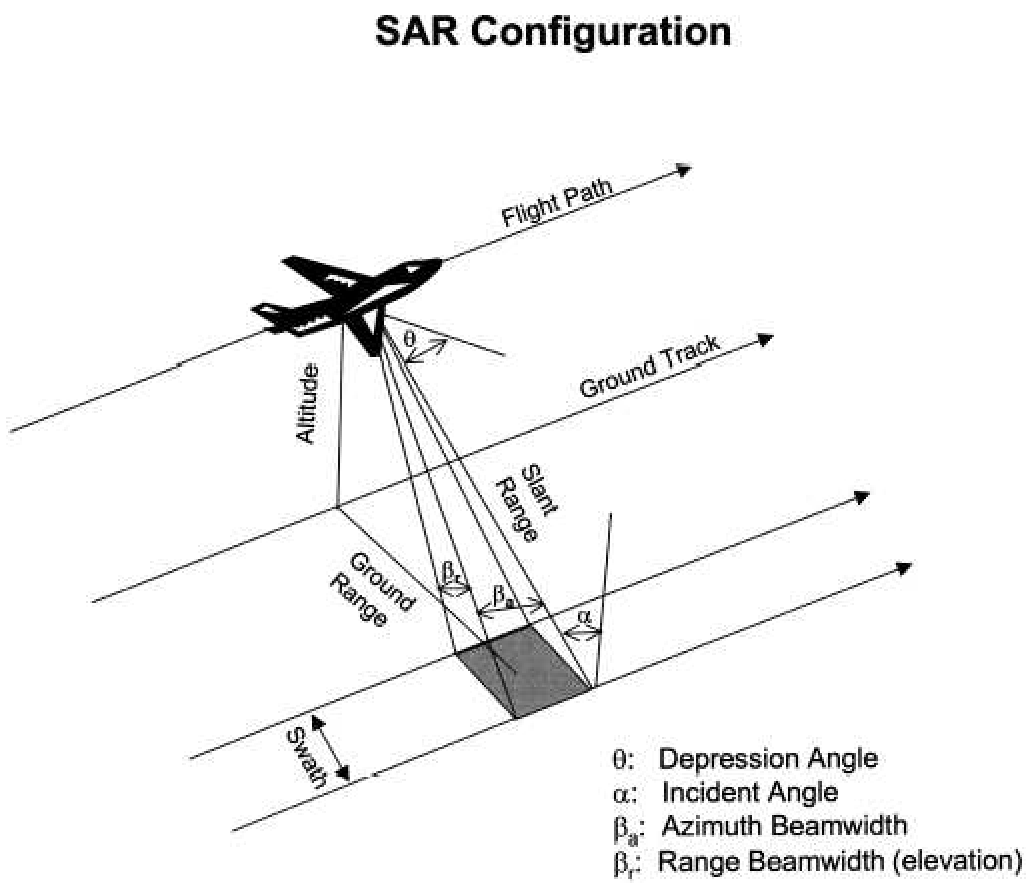
Being active, as well as operating in the microwave region of the electromagnetic spectrum, allows RADAR to operate day or night in all weather conditions (e.g., clouds, rain, snow). RADAR data can be used to map three-dimensional surfaces in the form of digital elevation models (DEMs), to measure surface changes in time, and to detect moving objects. Longer microwaves of RADAR can also penetrate the subsurface to detect buried features.

*Table 1: **Wavelengths of Variou**s Bands in the Microwave Range*

Band	Frequency (MHz)	Wavelength (cm)
Ka	40,000 – 26,000	0.8 – 1.1
K	26,500 – 18,500	1.1 – 1.7
X	12,500 – 8,000	2.4 – 3.8
C	8,000 – 4,000	3.8 – 7.5
L	2,000 – 1,000	15.0 – 30.0
P	1,000 - 300	30.0 – 100.0

The typical imaging geometry for a RADAR sensor is given in Figure 3. RADAR operates in a side looking mode; a swath is imaged well to one side of the aircraft or spacecraft. The depression angle (θ) is the angle between the horizontal and a line from the vehicle to specified location on the swath. The depression angle or its complement, the incidence angle (α), is commonly used to describe range geometry. The depression angle measurement is applied to airborne vehicles, while the incidence angle measurement is applied to spaceborne vehicles.

Figure 3: Typical RADAR Imagery Geometry



Swath width is dependent upon the altitude of the flight vehicle and is limited by the range beamwidth. The higher the altitude, the larger is the swath width for a given θ or α. In the azimuth or along track direction, there is no intrinsic geometric distortion from stationary terrain objects, because each object is imaged at the position of the SAR vehicle.

The intensity of reflected energy returning from a RADAR pulse is a function of the frequency of transmitted pulse, the polarity of the pulse, the incident angle of the RADAR beam, the roughness of the surface of the object or terrain, and the dielectric constant of the feature being imaged. The first three parameters (frequency, polarity, and angle) are controllable by the RADAR operator, while the last two, roughness and dielectric constant, are properties of natural or cultural features.

The transmitted RADAR wavelength, which typically ranges between 1 cm and 1 m, interacts with the roughness of the terrain according to a Rayleigh roughness criterion. Basically, if the granularity of the rough terrain is greater than 0.1 of the RADAR's wavelength, a significant return will occur. Polarization of the RADAR plays a role if a feature is aligned vertically or horizontally. Significant return from the subsurface can occur also when cross-polarized RADAR is used. The dielectric or electrical conductivity is important for metal objects because a high dielectric material reflects significant backscatter (i.e., RADAR return).

CATEGORIES OF RADAR SENSORS

Five categories of RADAR sensors are suitable for transportation studies. These five RADAR types include:

1) Fine resolution Synthetic Aperture RADAR (SAR);
2) Interferometric SAR (InSAR);
3) Pass to Pass Coherent Detection SAR;
4) Ground Moving Target Indicator (GMTI) RADAR; and
5) Ground Penetrating RADAR (GPR) Sensors.

Each of these five classes of RADAR systems has unique attributes that can be applied to transportation issues.

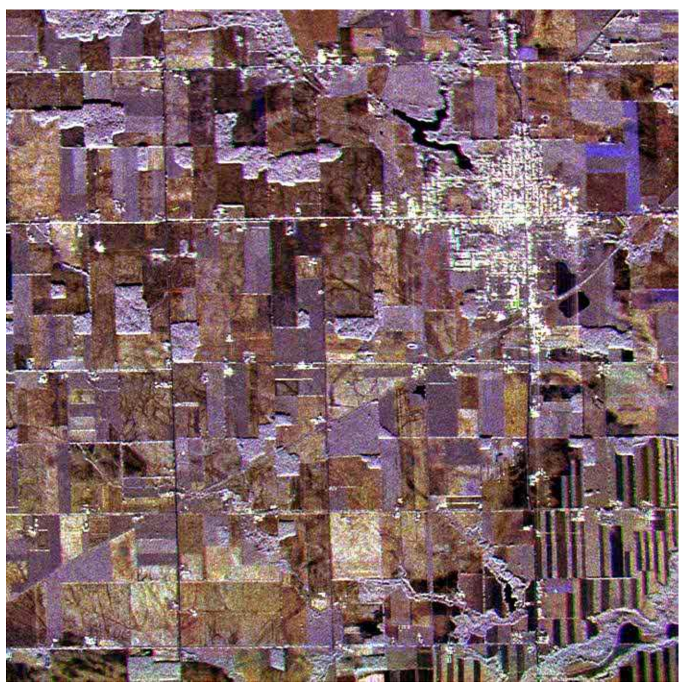
Synthetic Aperture RADAR

Spatial resolution is the ability of a remote sensing detector to discriminate close objects. An instrument that has "one-meter resolution" means that it can discriminate two objects that are one or more meters apart.

The spatial resolution of a stationary RADAR is limited by the diameter of its receiving dish (i.e., aperture), in which finer spatial resolution demands larger apertures. RADAR operated from a movable platform, such as an airplane, can use its forward motion as a way to simulate a dish with a much larger diameter, referred to as a *synthetic aperture*. The synthetic aperture RADAR (SAR) achieves high resolution by storing and processing Doppler shift data from multiple return pulses.

Spaceborne SARs have resolutions on the order of 25 meters, while aircraft and UAV SARs have resolution as fine as sub-meter. Satellite SARs typically map a swath width per pass of 100 km while aircraft and UAV have swaths on the order of 10-30 km. An example of a fine resolution image collected with airborne SAR is shown in Figure 4.

Figure 4: Fine Resolution SAR Map of Oxford County, Ontario from May 1990. *Source: Canada Centre for Remote Sensing*



In the transportation field, SAR could provide fine resolution synoptic maps of structures requiring detailed analysis, collected day or night in all weather conditions. This includes infrastructure maps, stationary or slow moving vehicle counts, and land cover. Because SAR utilizes Doppler to synthesize a long antenna, it cannot image both moving and stationary targets at the same time. SAR can also be used potentially to determine road surface roughness. Small-scale roughness can be measured with SAR if short wavelength, correctly polarized beams having optimum viewing geometry are used.

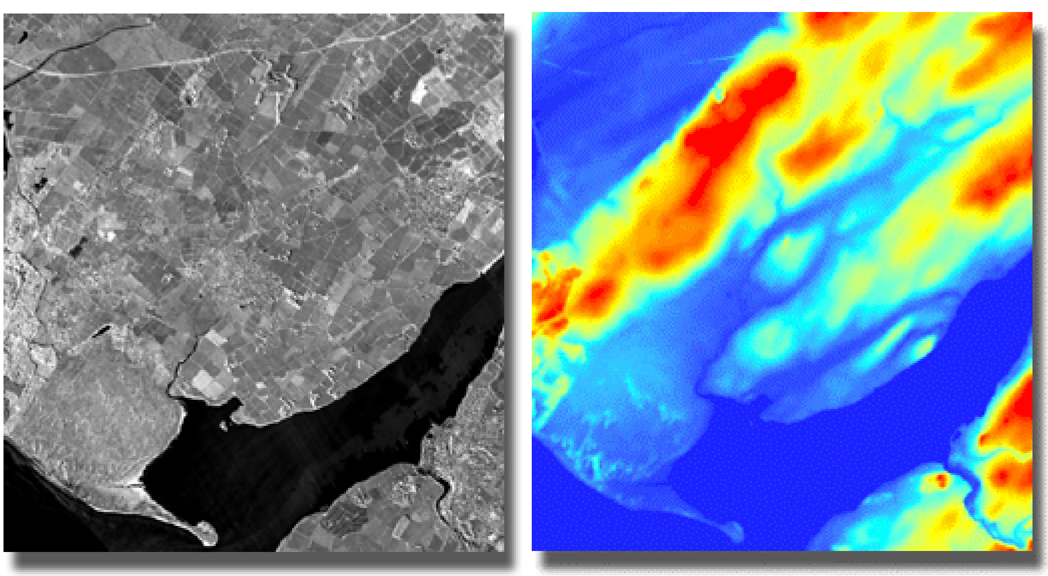
Interferometric Synthetic Aperture RADAR

Interferometric Synthetic Aperture RADAR (InSAR) is an aircraft- or satellite-based remote sensing method capable of measuring minute changes on the earth's surface. InSAR utilizes two antennas to image the same terrain area at slightly different ranges. The two near-simultaneously collected images are then processed coherently (i.e., the magnitude and phase value is retained). The two "coherent" images of the same area are then phase compared, where the slight difference in phase is related to a height difference.

InSAR techniques can be used to calculate flow rates of slow moving surfaces (e.g., glacier ice), to produce high spatial resolution topographic maps with accuracies of a meter or less, and to detect subtle changes in the height of terrain as in the case of subsidence before or after an earthquake.

One commercial company, called Intermap, operates the Star 3i InSAR consisting of a jet aircraft with X-band interferometric SAR systems. It produces sub-meter surface models (i.e., DEMs), as well as fine resolution SAR imagery. Examples of these data are shown in Figure 5. Intermap has also successfully demonstrated to the U.S. Department of Transportation that InSAR data can map roads overlayed on high-resolution topography.

Figure 5: Examples of Data from the Intermap Star3i InSAR System. *Fine resolution SAR imagery (left) and elevation data (right) Source: Intermap*



InSAR data have proved useful in locating high-risk landslide areas along highways. InSAR data could be a useful tool in any transportation application where fine detail topography or DEM data are required.

NASA's Space Shuttle Topographic Mission in 2000 was a highly successful application of InSAR technology that mapped most of the earth's land surface at 30-m resolution. Topographic data may be acquired for free through the U.S. Geological Survey (see http://edcsns17.cr.usgs.gov/srtmdted/).

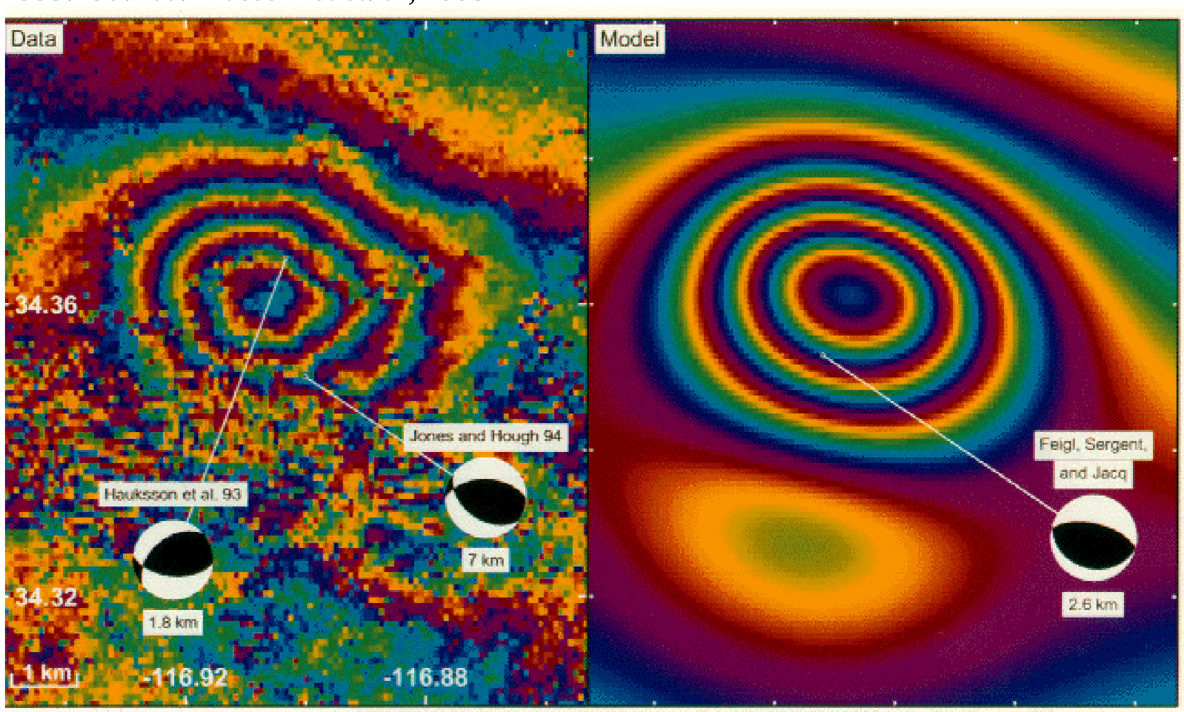
Pass to Pass Coherent Detection SAR

"Pass to Pass Coherent Detection" SAR is a subset of the larger InSAR category, in which data are collected for the same area over two or more time periods or passes to detect subtle movements or height changes. The individual passes are "coherently" processed and, as in the case of InSAR, are phase differenced where the phase information is used as an indicator of low velocities, topography or subsidence. Changes to terrain features between the passes, such as those due to geologic activity, can be detected with this method

The advantage of pass to pass coherent processing is that a conventional SAR satellite can be used. Though this technique has been demonstrated successfully from a single SAR satellite, pass to pass coherent processing from aircraft is difficult due to the navigational challenges of repeating the same observation geometry.

InSAR and pass to pass coherent detection SAR systems each have their advantages. Because InSAR is collected on one pass with two antennas, image registration and phase errors are not a problem and data processing is less complex. On the other hand, pass to pass coherent systems only require a single antenna for operation and can detect extremely small deviations over time.

Figure 6: Surface Deformation in Landers, California Due to Aftershocks. *ERS-1 pass to pass SAR satellite coherent detection, collected April 24, 1992, and June 18, 1993. Source: Massonnet et. al, 1993*



An example of pass to pass coherent detection SAR is shown in Figure 6 for land deformation due to an earthquake in Landers, California. Results before and after the event were obtained from the analysis of ERS-1 satellite data. Similarly, pass to pass coherent detection could prove useful to transportation applications that address subsidence or bulges in roadways, runways, or rail crossings.

Ground Moving Target Indicator RADAR

Ground Moving Target Indicator (GMTI) RADAR uses a moving target's Doppler RADAR return to distinguish it from surface clutter. This technique makes it possible to detect, locate, and track targets with the RADAR cross-section of vehicles throughout a large synoptic area when they are moving slowly on or just above the surface of land or water.

There are two types of GMTI RADAR: static (or snapshot) RADAR and dynamic (or continual observation) RADAR. Static RADAR provides an instantaneous picture of what was moving at a point in time with infrequent updates depicting moving target density. The Army OV-1 Mohawk's RADAR was an example of a static or snapshot GMTI RADAR. Development of RADAR capable of continual observation was key to the immense operational value of GMTI information. The E-8C Joint STARS' RADAR is an example of a dynamic GMTI RADAR system that provides periodic updates and allows precise tracking of a moving vehicle.

A RADAR system's ability to provide detailed, near-real time information on vehicular movement depends on its ability to reliably detect, accurately locate, and precisely track slow moving ground targets. GMTI can provide vehicle information, such as the length and the configuration of specific vehicles within a freeway, even when RADAR returns are temporarily interrupted by terrain screening or aircraft turns.

To provide precise, near-real time information on vehicles moving within a given area, a GMTI system must be able to generate and maintain numerous automatic tracks. The ability to do this depends on the system's performance in terms of the following metrics:

- Probability of Detection (PD) – the probability of detecting a given target at a given range any time the RADAR beam scans across its path;

- Vehicle Location Accuracy – a function of platform self-location performance, RADAR-pointing accuracy, azimuth resolution, and range resolution;

- Minimum Detectable Velocity (MDV) – the minimum rate of movement that can be detected by the sensor;

- Vehicle Range Resolution – the fidelity determining whether two or more targets moving in close proximity will be detected as individual targets;

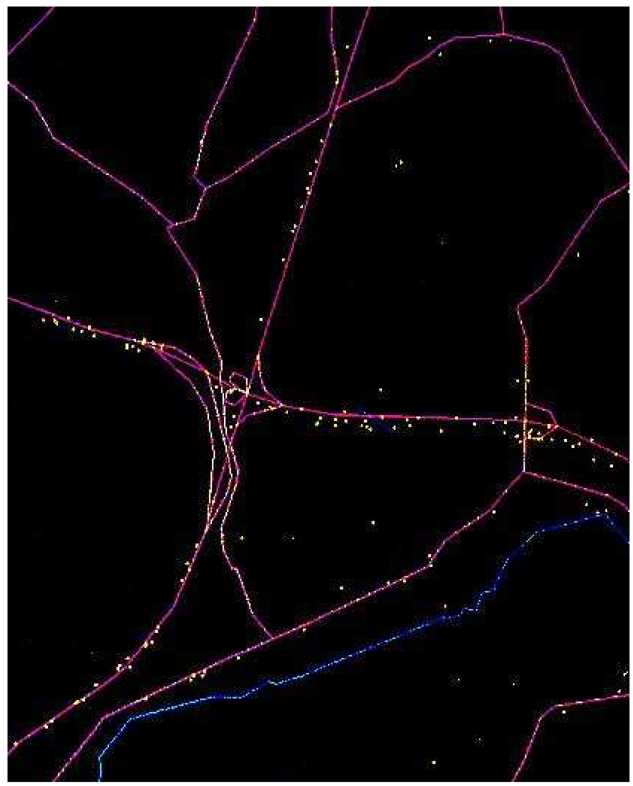
- Stand-off Distance – the distance separating a RADAR system from the area that it is observing;

- Coverage Area Size – the size of the area that the system can keep under continuous surveillance from a specific location. The earth's curvature and screening from terrain, foliage, and buildings cause system altitude to be a key factor determining coverage area – the higher the altitude, the greater the coverage.

- Coverage Area Revisit Rate – the frequency with which the RADAR beam passes over a given area.

If performance in even one of these GMTI metrics is degraded, the system will lose tracking performance and compromise the accuracy and timeliness of the ground picture.

Figure 7: An Output Map from a Ground Moving Target Indicator RADAR



The GMTI system's ability to collect high resolution, photo-like SAR still images concurrently is also vital to reliably tracking vehicular traffic. Collection of SAR images associated with GMTI information is essential for quickly locating vehicles that have stopped moving. Most GMTI RADAR systems can collect either GMTI or SAR information during the same mission, but not both simultaneously. JSTARS collects both SAR and GMTI data in near-simultaneous modes.

Figure 7 is an example of a GMTI map of vehicles along a road network. Note that GMTI RADAR provides an all-weather indication of vehicle numbers and speed along a road. Hence, any transportation application that requires vehicle counts and speed could benefit from GMTI.

Ground Penetrating RADAR

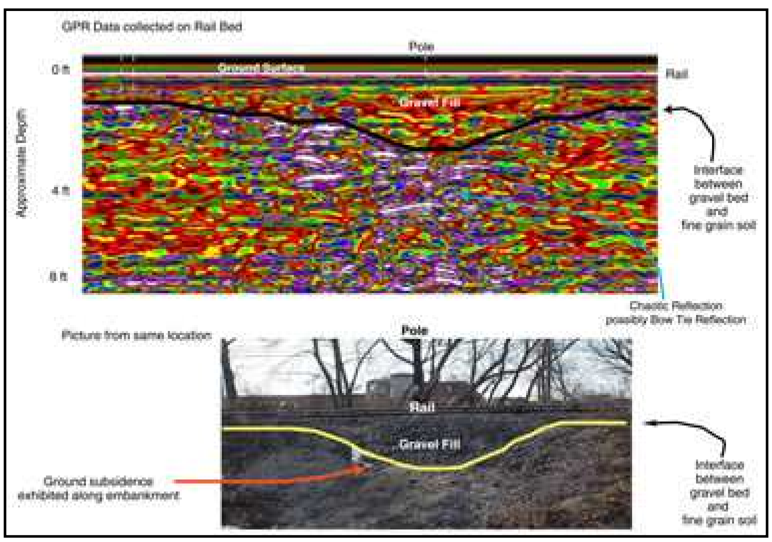
Ground Penetrating RADAR (GPR) uses electromagnetic wave propagation and backscattering to image, locate, and identify changes in electrical and magnetic properties in the ground. Practical platforms for the GPR include on-the-ground point measurements, profiling sleds, and near-ground helicopter or aircraft surveys. The Mirage Systems DSC901 is operated from a helicopter UAV.

GPR has the highest resolution of any geophysical method for subsurface imaging, approaching centimeters. Depth of penetration varies from meters to several kilometers, depending upon the materials' properties. Detection of a subsurface feature also depends upon contrast in the dielectric electrical and magnetic properties. Interpretation of ground penetrating RADAR data can lead to information about depth, orientation, size, and shape of buried objects. GPR has utility for a variety of transportation applications. These include: location of underground utilities (pipes, wires, fiber), soil types, and water.

During operation of a GPR, a RADAR pulse is modulated at frequencies from 100 to 1000 MHz, with the low frequency penetrating deeper than the high frequency, while the high frequency has better resolution than the low frequency. Basic pulse repetition rates are up to 128 Hz on a RADAR line profiling system on a sled or airborne platform. RADAR energy is reflected from both surface and subsurface objects, allowing depth and thickness measurements to be made from two-way travel time differences. At an airborne speed of 25 m/s (~56 mph) from an altitude of not more that three meters using a RADAR frequency of 75 Hz, line profile data can be collected up to four meters deep with five-centimeter resolution on 30-centimeter (one foot) grid centers. Playback rates of 1.2 km/min are possible for post-processing of the data.

An example of GPR data is present in Figure 8, showing a gravel fill layer under a railroad, having a thickness of 0.3 to one meter (one to three feet).

Figure 8: An Example of the Use of Ground Penetrating RADAR (GPR). *The image show gravel fill under a railroad bed. Source: Geophysical Survey Systems, Inc.*



Sensor Platforms

Specific parameters of a broad selection of RADAR systems are presented in Tables 2 – 5. Table 2 lists satellite-based systems, Table 3 provides systems flown on manned aircraft, Table 4 lists sensors designed for UAVs, and Table 5 shows a number of prominent GPR systems.

Of the 10 past or present orbiting systems listed in Table 2, including the Space Shuttle missions, only two are operational – RADARSAT-1 and ENVISAT. These two robust systems are good platforms for performing pass to pass coherent detection. These operational satellites will soon be joined by new systems, including RADARSAT-2 and ALOS/PALSAR. The ALOS/PALSAR mission, a project of the National Space Development Agency of Japan (NASDA), will have polarimetric SAR capability, which will provide unique information on wetlands, other vegetation types, and subsurface structures.

For transportation applications airborne platforms are best for fine resolution SAR mapping, InSAR topographic mapping, GMTI, and GPR. The lower altitude of aircraft provides greater detail than that achievable from orbital platforms. After FAA problems are solved, UAVs offer unique long-term observation capabilities, which would be especially advantageous for border crossings, homeland security, and intelligent transportation systems.

Table 2: Satellite RADAR Systems (NA = Not Available)

Satellite	Agency	Frequency (GHz)	Wavelength (cm)	Polarization	BW (MHz)	Pulse Duration (μsec)	Pulse time - BW product	PRF (Hz)	Antenna Beam Width (deg)		Antenna Pointing Angle (deg)
Past and Present Satellites											
ALMAZ	MOM (Russia)	2.8	10	HH	10.5	~30	250	1,200	6	1	20 - 70
ENVISAT	ESA	5.331	5.7	HH, VV, HV	100	33	1,200	1,750	6	1	15 - 45
ERS-1/2	ESA	5.3	5.7	VV	19	37 12.3 (Wave mode)	703	1,700	6	1	23 at mid swath
JERS-2	NASDA (Japan)	1.275	2.35	HH	15	34	700	1,500	6	1	35
RADARSAT-1	CCRS (Canada)	5.2	5.7	HH	12	27.9	250	1,315	6	1	20 - 45
Seasat	NASA (USA)	1.275	2.35	HH	19	33.8	642	1,647	6		19- 25
Space Shuttle Missions											
SIR-A	NASA (USA)	1.275	2.35	HH	6	33	198	1,110	6	1	50 - 55
SIR-B	NASA (USA)	1.275	2.35	HH	12	33	396	1,110	6	1	15 - 60
SIR-C	NASA (USA)	5.3	5.7	HH, VV, HV, VH	6, 12, 24	33	200 - 600	1,100 - 1,800	6	1	15 - 75
		1.27					198 - 594	1,110			
SRTM	NASA (USA)	1.275	5	HH, VV	24	35	500	1,350	6	1	10 - 60
Future Satellites											
ALOS/PALSAR	NASDA (Japan)	1.27	25	HH, VV, HH & HV, VV & VH	20	35	700	1,500	6	1	10 - 51
		1.27	25	HH, VV	10	35	700	1,500	6	1	10 - 50
RADASAT-2	CCRS (Canada)	5.2	5	HH, VV, HV, VH	100	30	250	1,350	6	1	10 - 70
TerraSAR-X	Germany	8 - 12.5	3	HH, VV	100	35	1200	1,500	6	1	20 - 50

Table 2: (continued)

Satellite	Slant Range Resolution (m)	Azimuth Resolution (m)	Swath Width (km)	Platform Altitude (km)	Nominal Range (km)	Orbital Inclination (deg)	Orientation	Node	Data Recorder	Launch Date	Status
Past and Present Satellites											
ALMAZ	15 - 30	15 (4 look)	40	350	500	73	Right/Ascending Left/Descending	Sun	Digital and Optical	1991	Failed
ENVISAT	30	30	100 - 405	800	800	98	Right/Left	Sun	Digital	2002	Operational
ERS-1/2	8 (30 m ground range)	30 (4 look)	100	845	900	97.5	Right/Left	Sun	Digital	1991 & 1995	On orbit - storage
JERS-2	18	18 (3 look)	100	568	700	97.5	Right	Sun	Digital	1992	Failed
RADARSAT-1	12.5	10 (1 look)	50 - 500	8,000	1,220	98.5	Right	Sun	Digital	1995	Operational
Seasat	8	6 (1 Look)	100	800	850 (at 20° incident angle)	108	Right	Sun	Digital via telemetry link	1978	Failed
Space Shuttle Missions											
SIR-A	40	40	55	280	365 (at 50° incident angle)	60	Right	NA	Optical	1981	Completed
SIR-B	25	17 - 58	20 - 50	225	300 (at 50° incident angle)	57	Right	NA	Digital	1984	Completed
SIR-C	10 - 30	10 - 30	20 - 100	250	Variable	57	Right	NA	Digital	1984, 1993, 1994, 1996	Completed
SRTM	30	30	100	225	300	57	Right/Left	NA	Digital	2000	Completed 11-day mission
Future Satellites											
ALOS/PALSAR	10	10	70	700	750	98	Right/Left	Sun	Digital	(2005)	Late calendar launch
	100	100	250 - 350								
RADASAT-2	3 - 100	3 - 100	20 - 500	798	850	98.6	Right	Sun	Digital	(2006)	Prelaunch
TerraSAR-X	1	1	5 x 10	514	550	98	Right/Left	Sun	Digital	(2006)	Prelaunch

Table 3: RADAR Sensors on Manned Aircraft (NA = Not Available)

System	RADAR Type	Frequency (GHz)	Wavelength (cm)	Polarization	BW (MHz)	Pulse Duration (μsec)	Swath Width (km)	Platform Velocity (m/s)	Platform Altitude (m AGL)
Intermap STAR-3i	SAR Mapping / InSAR	9.5675	3	HH	67.5	2.2	5, 10	200	6,500 - 9,500
Intermap TopoSAR	SAR Mapping / InSAR	8 - 12.5	3	HH	NA	3	2, 4, 7	110	3,500
		0.3 - 1.0	74	HH, VV, HV, VH			4		
GEOSAR	SAR Mapping / InSAR	8 - 12.5	3.87	VV	80	3	20	205	10,000 - 12,000
		0.3 - 1.0	86	HH, VV, HV, VH	160				
Canadian Centre for Remote Sensing C/X SAR	SAR Mapping / Coherent	5.3	5.66	HH, VV Pol	26.3, 8.3	2 - 3	NA	75	15,000
		9.25	3.24	HH, VV Pol	31.2, 7.5				
NASA DC8	SAR Mapping / Coherent / InSAR	1248.75	24.02	HH, VV, HV, VH	19	11.25	30	260	15,000
		5298.75	5.662						
		438.75	68.38						
General Dynamics DCS	SAR Mapping / Coherent / InSAR	8 - 12.5	3	VV, HH, VH	100	3	15	75	15,000
Sandia Twin-Otter (VHF/UHF)	SAR Mapping / Coherent / InSAR	125 - 950	60	VV, HH	100	1 - 3	2 - 6	35 - 70	3,500
		7.5 - 10.2	3	VV, HH					
		14 - 16	1	VV, HH					
		32.6 - 37	0.89	VV					
JSTARS	GMTI	8 - 12.5	3	HH	100	NA	25	280	12,800

Table 4: RADAR Sensors on UAVs

Sensor	Vehicle	Mode	Frequency (GHz)	Polarization	Transmitter Peak Power (watts)	Antenna Pointing Angle (deg)	Slant Range Resolution (m)	Swath Width (km)	Ground Range (km)	Platform Velocity (m/s)	Platform Altitude (m AGL)
Global Hawk SAR	Global Hawk	Strip	8.7	H	1300	45 - 135	1	10	20 - 200	180	20,000
		Spot	8.7	H	1300	45 - 135	0.3	2			
Lynx	I-Gnat, Predator, Prowler	Strip	15.2 - 18.2	H	1200	40 - 130	0.3 - 3.0	5	7 - 30	33 - 43	4,500
		Spot	15.2 - 18.2	H	1200	40 - 130	.1-3	5	4 - 25		
TESAR	Predator	Strip	16	V	1050	45 - 135	.03 - 1	0.8	4.6 - 11	41 - 69	2,000 - 6,000
TUAV SAR	Outrider/Shadow 2000	Strip	16	H	530	45 - 135	1	1.5	3 - 10	30 - 50	1,800 - 3,700
		Spot	16	H	530	45 - 135	0.3 - 1.0	3			

Table 5: Ground Penetrating RADAR Systems

Manufacturer	Model	Frequency (MHz)	Bandwidth (MHz)	Wavelength (m)	Approximate Depth (m)*	Application
Geo-Centers	EFGPR	1,250	+/-1,000	0.23	1	Landmines
Geophysical Survey Systems	SIR-3000	2,200	+/-1,000	0.14	0.75	Road, concrete
		1,000	+/-1,000	0.30	1.5	Road, concrete
		1,500	+/-1,000	0.20	1	Road, concrete
		900	+/-1,000	0.33	1.5	Road, concrete
		400	+/-1,000	0.75	4	Utility
		270	+/-1,000	1.10	6	Utility
		200	+/-1,000	1.50	7	Utility, archaeological, forensic
		100	+/-1,000	3.00	20-Oct	Utility, archaeological, forensic
		16-80	+/-1,000	3.75 - 18.75	25-30	Utility, archaeological, forensic
IDS	RIS	25 - 2,000	+/-13,000	0.15 - 12.0	20 - 30	Buried features
Mirage	DCS 901	250 - 3,000	500	0.10 - 1.20	1 - 5	Utility, Cables
Sensors & Software	Noggin 1000	750	500	0.40	1 - 2	Utility, Cables
	Noggin 500	500	500	0.60	2 - 3	Utility, Cables
	Noggin 250	250	250	1.20	5	Utility, Cables
	pulseEKKO 100	12.5	12	24.00	10 - 30	Utility, Cables
		25	26	12.00	8	Utility, Cables
		50	50	6.00	4	Utility, Cables
		100	100	3.00	2	Utility, Cables
		200	200	1.50	3	Utility, Cables
	pulseEKKO 1000	110	110	2.73	5 - 10	Utility, Cables
		225	250	1.30	5	Utility, Archaeological, Forensic
		450	375	0.67	1	Utility, archaeological, forensic
		900	900	0.33	1	Road, concrete
		1,200	1,200	0.25	1	Road, concrete
Systems Planning Corporation	MKV	150-450	+/-1,000	0.67 - 2.0	5	Buried features

*** For typical soils**

TRANSPORTATION APPLICATIONS

Each of the five types of RADAR systems discussed in the previous section operate from a preferred platform (i.e., satellite, manned aircraft, or UAV), or in the case of the SAR mapper operate, from all three types of platforms. InSAR systems can operate from space as in the case of the Space Shuttle RADAR Topographic Mission (SRTM). However, the more efficient platform for InSAR is jet aircraft. Coherent SAR change detection is a satellite-driven application that has been successfully demonstrated using RADARSAT-1 and ENVISAT data. GMTI RADAR systems are operated by the military from long flight duration aircraft. UAVs also have been used as platforms for GMTI in remote parts of the world. GPR systems may be operated from the ground level or from low-flying aircraft, including UAVs.

The FAA restricts the use of UAVs in the continental U.S. The FAA's concerns include, aircraft to aircraft collision, and UAVs becoming out of control from their flight controllers. Until these concerns are overcome, which is estimated to be within three to five years, UAV operational use in the United States will be severely limited.

Table 6 is an initial attempt to begin the process of matching RADAR types to the eight MDOT applications areas. This table will be updated after the results of the focus group needs are analyzed. Examination of the table clearly indicates the role that high resolution SAR mapping can provide in addressing MDOT needs. InSAR, operated from aircraft, can provide critical high definition topography or a DEM, which is useful information for asset management, environmental data needs, as well as HAZMAT routing and safety concerns. Pass to pass coherent SAR has been shown to be an extremely useful tool when subtle changes in terrain height need to be monitored, hence its particular use in asset management, environmental needs an inter and multi-model transportation. Ground moving target indicator RADAR is used extensively by the military to map target vehicles moving on the ground. This technology is mature and offers the potential to synoptically map vehicle number and speed day or night in all weather conditions. This technology has obvious utility to a number of MDOT transportation application areas. The fifth type of remote sensing system, ground penetrating RADAR, maps features below the surface and should prove useful in the areas of asset management, environmental data needs, and inter- and multi-modal transportation. A discussion of each of the eight MDOT application areas follows.

Asset Management

Asset management is a major activity of transportation officials in which large volumes of data must be collected frequently. Evaluating the condition of assets allows managers to set priorities and estimate costs. RADAR data can support this activity.

Surface roughness of roads and the mapping of road corridors can be done with SAR mapping instruments. Topographic data from InSAR sensors can provide high spatial resolution road grade maps. Pass to pass coherent detection, which identifies surface changes over time, can be used to map pothole changes and areas where roads are sinking. GMTI RADAR has practical uses for estimating vehicle counts and speed. GPR can detect subsurface problems and buried utilities.

Table 6: Potential Utility of RADAR Systems for MDOT Application Areas (NA = Not Applicable)

MDOT Application / RADAR Types	Asset Management	Environmental Data Needs	Inter- and Multi-Modal Transportation	HAZMAT Shipments	Traffic Safety and Congestion	Border Crossing	Homeland Security	ITS / Operations
SAR Mapping (satellite, manned aircraft, UAV)	Road roughness, corridors	Wetlands, corridors, right-of-ways, land cover, forest inventory	Line of sight at railroad crossings	Optimum routes, hazards en route, RADAR tags	Vehicle type	Vehicle counts and type	Vehicle type counts, corridor inspection	Base map, RADAR tags
InSAR (manned aircraft)	High resolution road grade maps	Topography, DEMs, feature classification	NA	Optimum routing	Line of sight, steep grades, slope stability	NA	NA	High resolution topography, base maps
Pass-to-Pass Coherent Detection (satellite)	Potholes, Sinking roads	Subsidence, elevation increase, anthropogenic change detection	Runway and railroad deterioration	NA	Slope stability	NA	Change detection of area	NA
GMTI (manned aircraft, UAV)	Vehicle counts and speed	Vehicle counts	NA	NA	Vehicle counts and speed	Vehicle counts and speed	Vehicle counts and speed	Synoptic vehicle counts and speed
Ground Penetrating RADAR (manned aircraft, ground)	Under road problems, buried utilities	Subsurface mapping (pipes, tunnels, water channels)	Underground utilities, under runway problems	NA	NA	NA	NA	NA

Environmental Data

Environmental reports are often required for transportation construction projects. RADAR provides an effective tool for gathering environmental information, and can assist the engineer in selecting routes and developing mitigation plans.

Wetlands, corridor and right-of-way features, land cover, and forest inventories can be evaluated with SAR mapping techniques. InSAR can provide additional data on topography with the collection of DEM data and perform feature classification. Certain environmental concerns, such as subsidence, elevation increase (geologic activity), and changes due to anthropogenic causes can be detected with pass to pass coherent RADAR techniques. The volume of traffic as measured by vehicle counts is may be measured with GMTI RADAR. As with asset management GPR can detect subsurface structures, such as pipes, tunnels, and water channels.

Inter- and Multi-Modal Transportation

Inter- and multi-modal transportation involves air, rail, and water systems with associated infrastructure that requires monitoring, maintenance, and new construction. Small degrees of deterioration or movement in airport runways and railroads can be monitored with pass to pass coherent detection. During maintenance or new construction, GPR is a useful tool for detecting underground utilities or for examining problems underneath runways.

The interface of different modes of transport, such as vehicular and rail, raises special safety issues. For example, railroad crossings are required to have a minimum line of sight to ensure safety. SAR mapping can be especially important for detecting right-of-ways and potential visual obstructions.

HAZMAT Shipments

Transporting hazardous materials safely requires the selection of appropriate transportation routes and being prepared to respond to emergency situations. Both SAR mapping and InSAR data can help identify the optimal HAZMAT routes to minimize public risk. Continuous monitoring with SAR could identify transportation hazards en route to avoid accidents.

A potential technology could involve the use of special RADAR-reflective tags that could be embedded on HAZMAT vehicles. This would facilitate the real time tracking and identification of these vehicles with SAR sensors.

Traffic Safety and Congestion

Few transportation issues are more prominent than traffic safety and congestion, both in the minds of the public and of government officials. RADAR can collect data that help engineers understand safety hazards and congestion problems more clearly.

Because SAR mapping is very sensitive to the geometry of metallic objects, it can categorize vehicle types. Topographic information from InSAR systems can provide information on lines of sight, map roads with steep grades, and identify hazardous slopes. Pass to pass coherent RADAR can monitor slope stability over time in highway corridors. GMTI RADAR is a valuable tool for collecting information on vehicle counts and speed, which can augment data collected *in situ* by highway video cameras.

Border Crossing
Efficient, safe transportation operations at international border crossings are crucial to the economies of Michigan and Canada. As transportation volume and security concerns grow RADAR may be an effective tool for monitoring ports-of-entry. SAR mapping can provide vehicle counts in border crossing queues. GMTI RADAR can be used to monitor vehicle speed and traffic volume.

Homeland Security
Homeland security requires control of anthropogenic and natural threats to public safety. As such, it shares many of the challenges associated with border crossings, HAZMAT shipments, and environmental data. RADAR can be an important component of a security monitoring program. SAR mapping can contribute to routine corridor inspections and scrutinize potential threats. Pass to pass coherent detection may be used to sense changes in an area over time.

During response to an emergency situation, RADAR systems, such as SAR mapping and GMTI, can be activated to perform vehicle counts, type, and speed. This could be particularly valuable during an evacuation crisis. SAR mapping can detect flooded areas or help evaluate structural damage.

Intelligent Transportation Systems / Operations
The goal of intelligent transportation systems (ITS) is to improve utilization of transportation resources through new technologies. SAR mapping systems have demonstrated their utility for creating transportation base maps. Likewise, InSAR can capture topographic data, providing three dimensions to transportation network maps. GMTI and collect vehicle counts and speed for inputs into ITS models.

If RADAR-reflecting tags were placed on vehicles, such as freight trucks, SAR mapping technology could determine the distribution and densities of these vehicles to improve traffic flow and safety.

CONCLUSIONS

As discussed above, RADAR systems offer a broad range of remote sensing capabilities that can be applied to transportation problems, such as vehicle movements, mapping of topographic and cultural features, road conditions, slope movement, and detection of subsurface structures. RADAR gives a synoptic view of large territories in all kinds of weather, including cloudy, rainy, and foggy conditions. Given that RADAR is especially sensitive to metallic objects offers distinct advantages for detecting vehicles.

Due to the high spatial resolution demands of most transportation applications, airborne sensors provide many advantages over satellite systems. The one arena in which satellite systems have an advantage is for pass to pass coherent detection. The upcoming ALOS/PALSAR system may offer some advantages for mapping habitat types and subsurface features.

In the future, installation of unique RADAR-reflecting tags on vehicles could provide real time information for an ITS. Improvements in flight safety features of UAVs could help transfer SAR capabilities from the military domain to the public sector.

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APPENDIX A: Acronyms and Abbreviations

DEM	Digital elevation model
EM	Electromagnetic
FAA	Federal Aviation Administration
GHz	Gigahertz (1 billion cycles/second)
GMTI	Ground moving target indicators
GPR	Ground penetrating RADAR
HAZMAT	Hazardous materials
InSAR	Interferometric RADAR
m/s	Meters per second
MHz	Megahertz (1 million cycles/second)
MDV	Minimum Detectable Velocity
NASDA	National Space Development Agency of Japan
PD	Probability of detection
RADAR	Radio detection and ranging
SAR	Synthetic aperture RADAR
SRTM	Shuttle RADAR Topographic Mission
UAV	Unmanned aerial vehicle